YITP workshop: “Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives”
@Kyoto University
December 7–10

Systematic Study of Acceleration Efficiency in Young Supernova Remnants

(arxiv:2012.01047)

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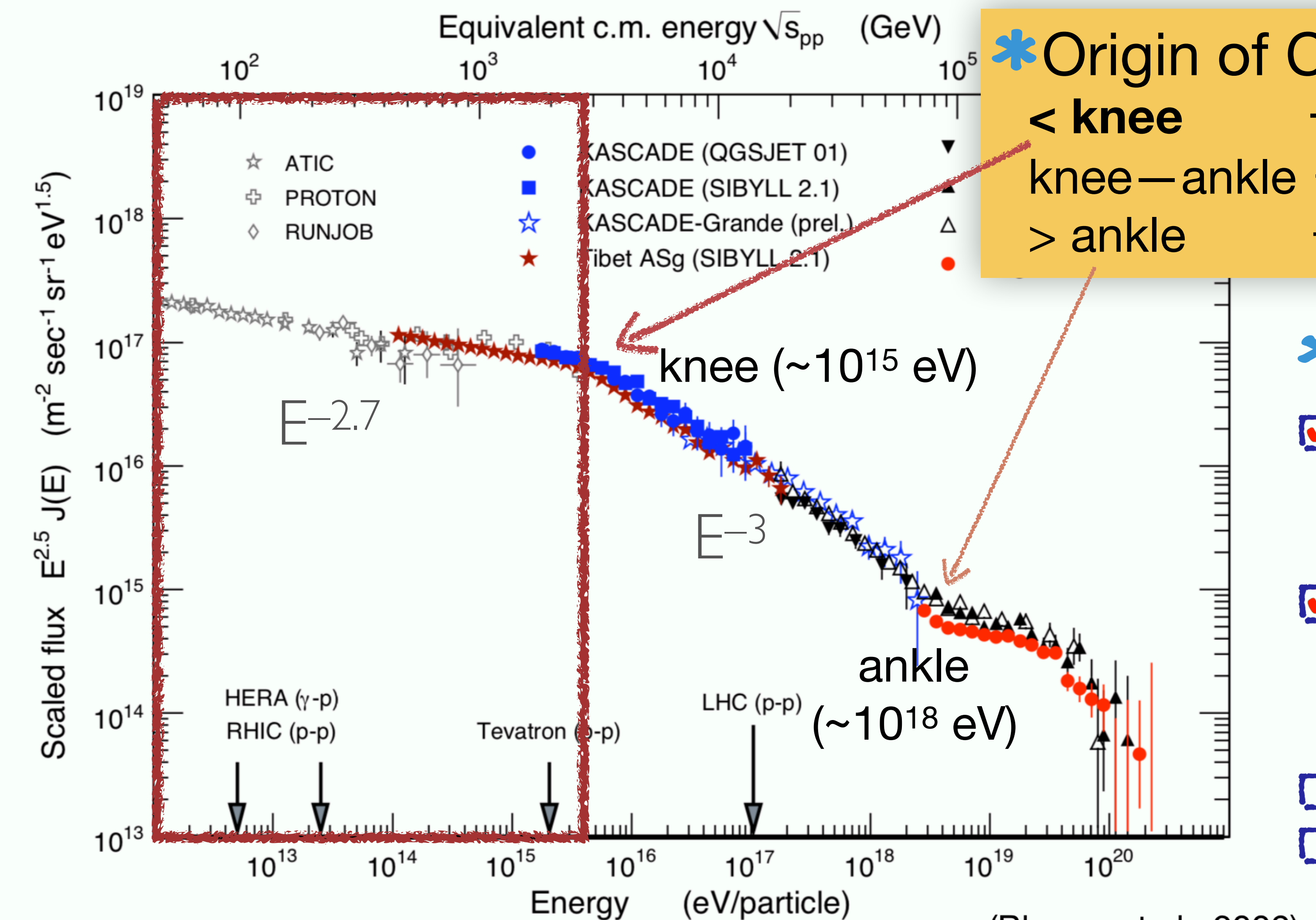
Cosmic Ray: CR

- ☑ High-energy particles in space
- ☑ Protons (~90%), He nuclei (~10%), electrons, and heavy nucleon…
- ☑ CR spectrum has two breaks; knee and ankle



(Blumer et al., 2009)

✱ Origin of CRs

- **< knee → Galactic SNRs**
- knee—ankle → Unknown
- > ankle → Extragalactic?

✱ SNR paradigm

- ☑ Energy budget
  E_{CR}/E_{SN}~10%
  → U_{CR} (1 eV/cc)
- ☑ Spectral shape
  Standard DSA
  → Power-law
- ☐ Max. energy?
- ☐ Acceleration mechanism?

Acceleration efficiency

Acceleration timescale: $t_{\rm acc} \propto \dfrac{E\eta}{v_{\rm sh}^2 B}$

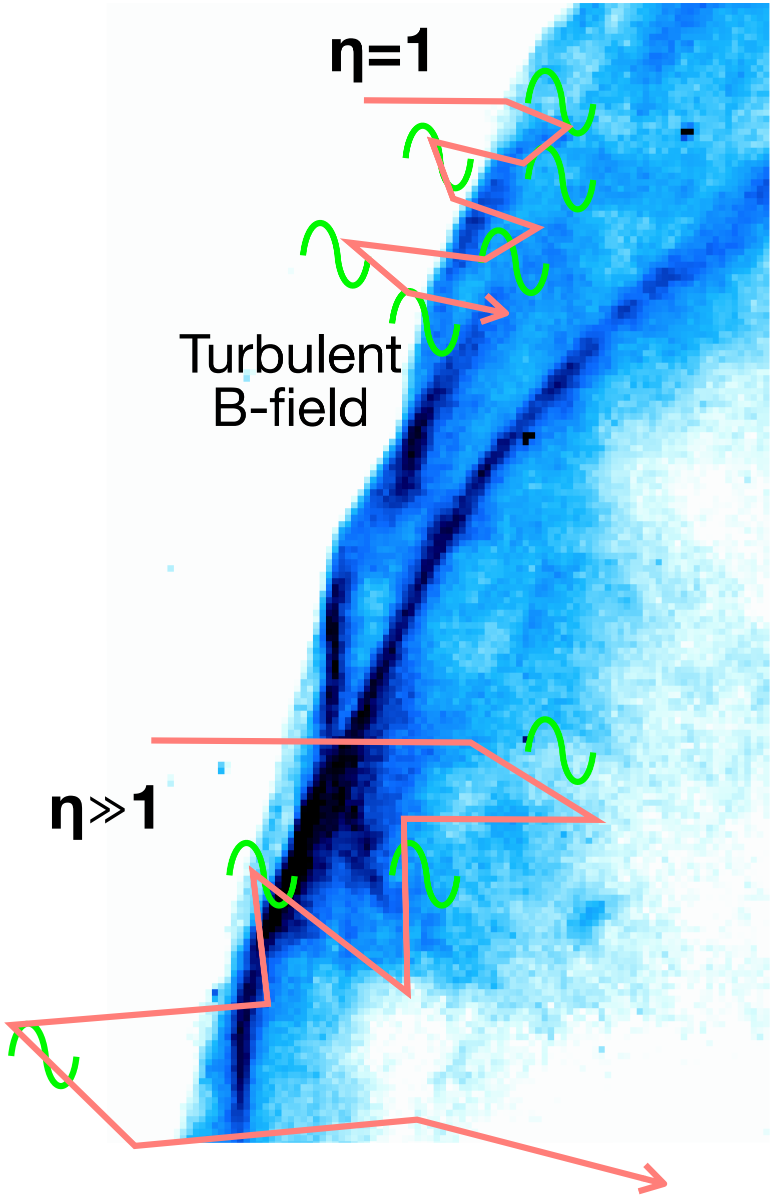
"Bohm factor" η

Acceleration efficiency

η = (particle m.f.p.) / (gyroradius)

$\eta \sim (B_0 / \delta B)^2$

	η=1 (Bohm limit)	η ≫1
m.f.p.	smallest	large
$t_{\rm acc}$	shortest	long
B-field	turbulent	less turbulent
Acceleration	efficient!	inefficient



How to derive η from observations?

Acceleration timescale: $t_{\rm acc} \propto \frac{E\eta}{v_{\rm sh}^2 B}$

Cooling (synchrotron) timescale: $t_{\rm synch} \propto \frac{1}{EB^2}$

Cooling-limited acceleration:

$t_{\rm acc} \approx t_{\rm synch}$ gives cutoff energy

Electron cutoff: $E_c \propto v_{\rm sh} B^{-1/2} \eta^{-1/2}$

Synchrotron X-ray cutoff: $\varepsilon_c \propto E_c^2 B \propto v_{\rm sh}^2 \eta^{-1}$

$\varepsilon_0 \propto V_{\rm sh}^2/\eta$

If we measure **cutoff** and **shock speed**, we can obtain **η**!

- cutoff → Spectral fitting
- shock speed → Proper motion measurement
- η → this work

※ More detailed analytical calculations are done by Zirakashvili & Aharonian 2007

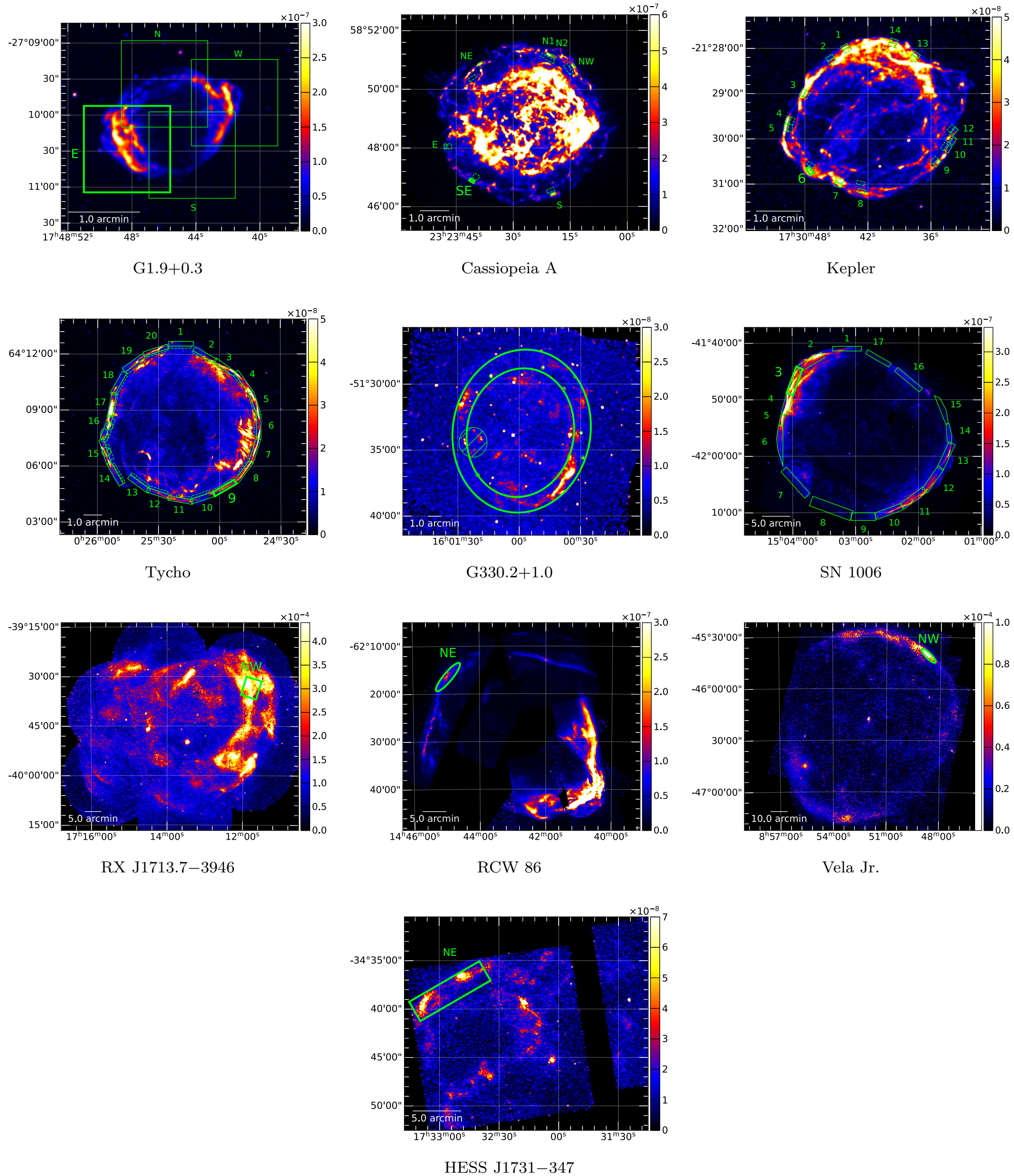
Young SNRs in X-ray

- Systematic analysis of young Galactic SNRs:
  - G1.9+0.3, Cassiopeia A, Kepler, Tycho, G330.2+1.0, SN1006, RX J1713.7–3946, RCW 86, Vela Jr., HESSJ 1731-347 (, SN 1987A)

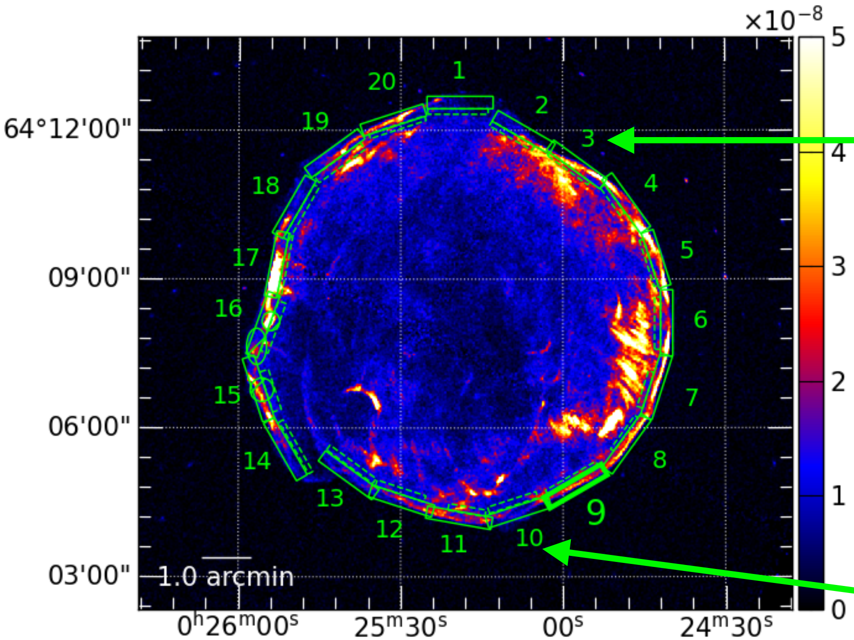
Assume the hard continuum is synchrotron for SN1987A

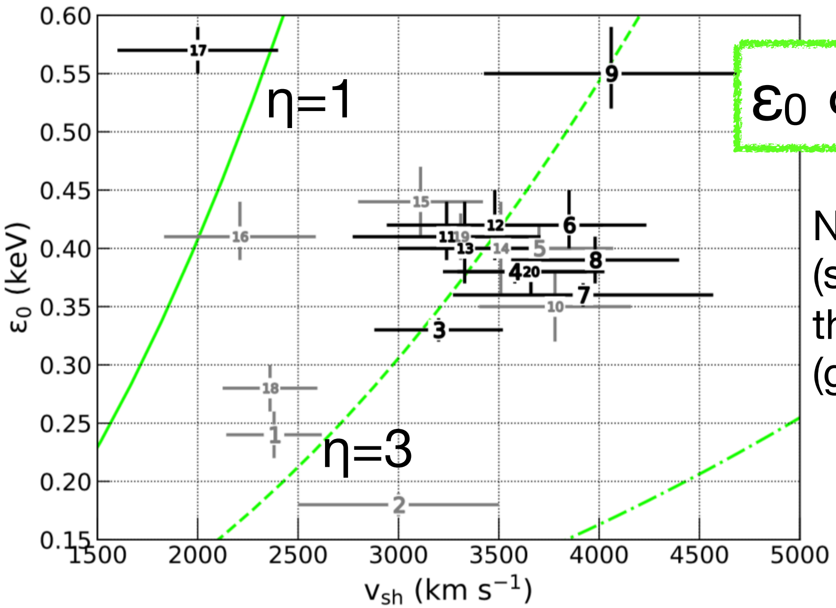
- Spectral fitting:
  - soft X-ray: Chandra/Suzaku
  - hard X-ray: NuSTAR
  - Model: ZA07

- Derived cutoff energy + known shock speed → acceleration efficiency (η)



Tycho

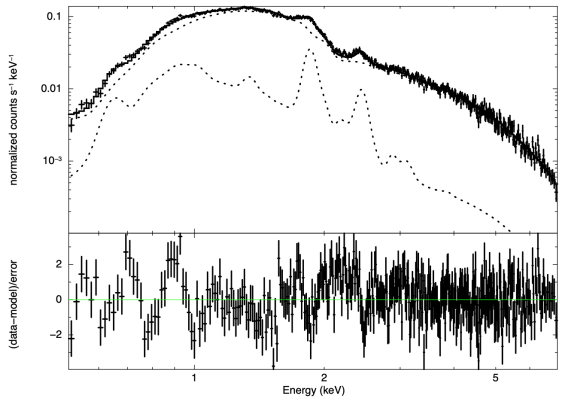




$\varepsilon_0 \propto V_{sh}^2/\eta$

Nonthermal-dominated (shown in black)
thermal-dominated (gray)

Nonthermal-dominated



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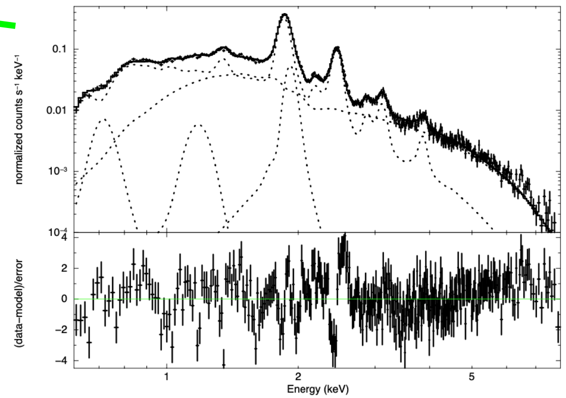
Thermal-dominated



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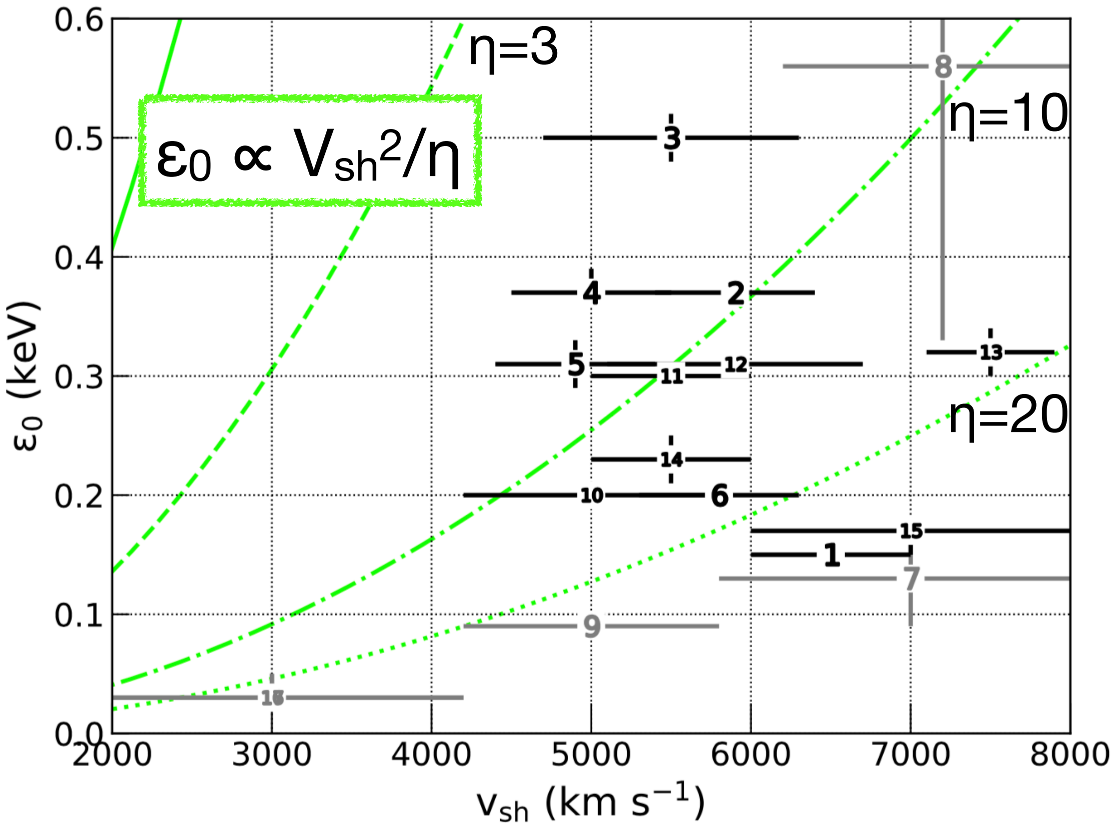
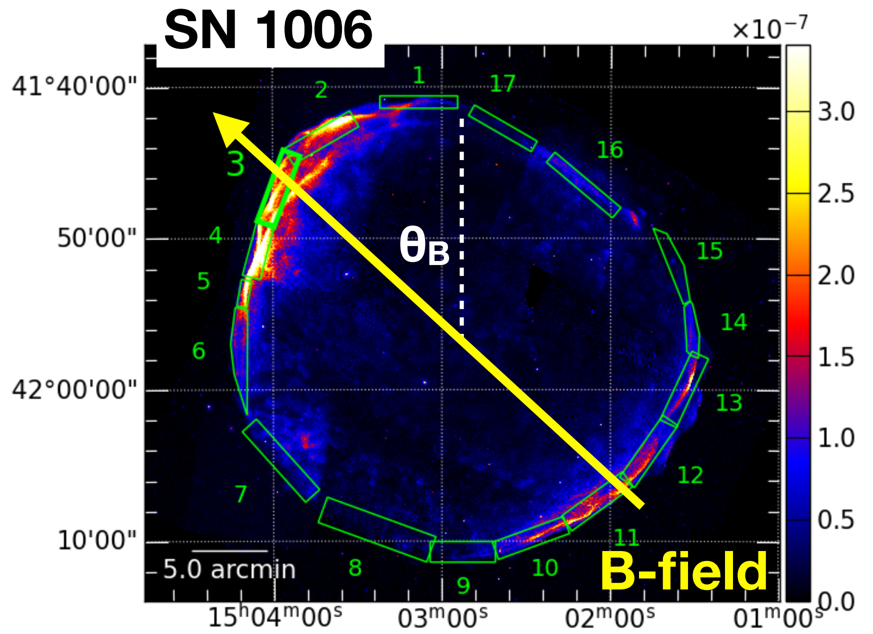
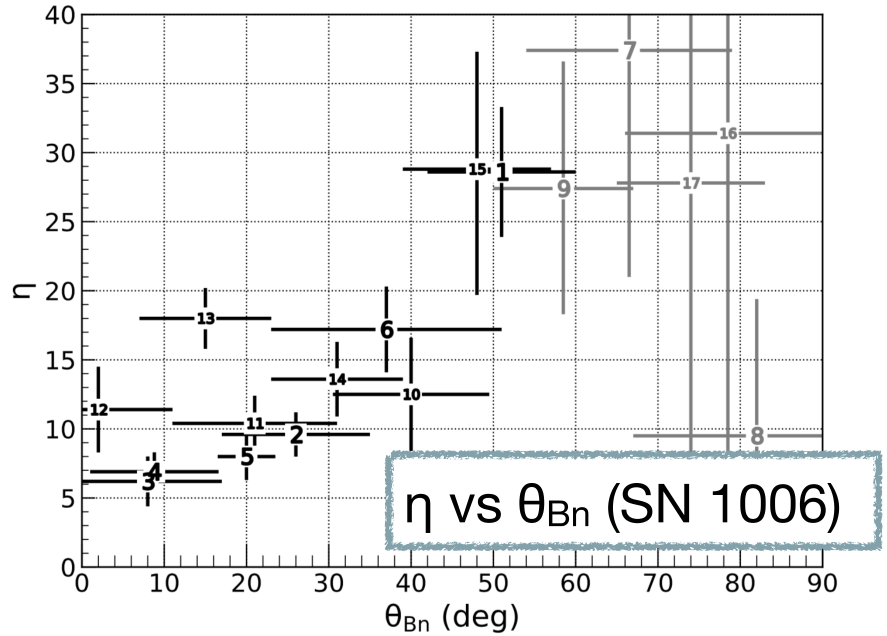
‘Standard’ acceleration with constant η = 3–5

SN 1006

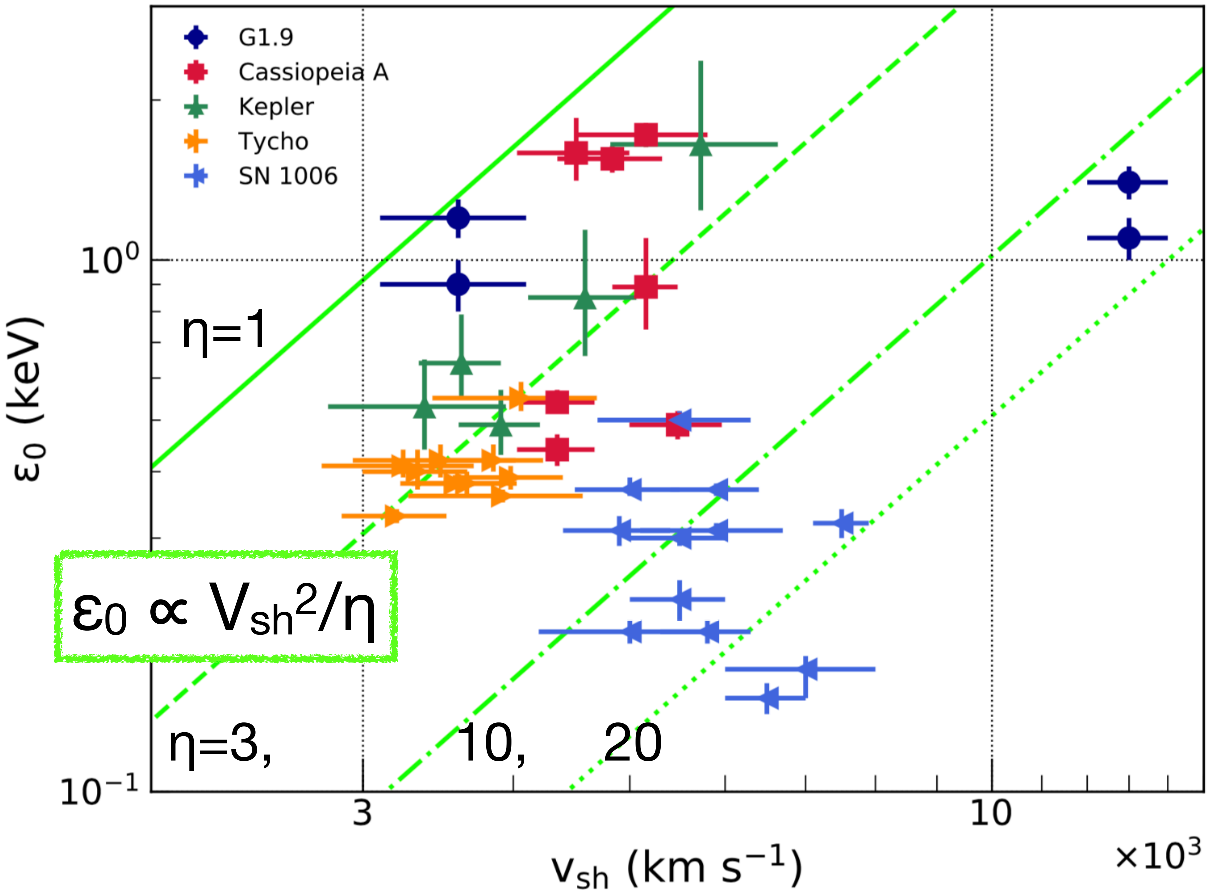




- Inverse trend of the theoretical curve
- Acceleration affected by B-field; shock obliquity (e.g., Miceli+ 09)
- →Perpendicular shock is more efficient?



E_0 v.s. V_{sh} (summary)



Kepler
Constant acc. efficiency

Tycho
Constant acc. efficiency

Cassiopeia A
Affected by ambient density

SN 1006
Affected by B-field obliquity

G1.9+0.3
Young accelerator

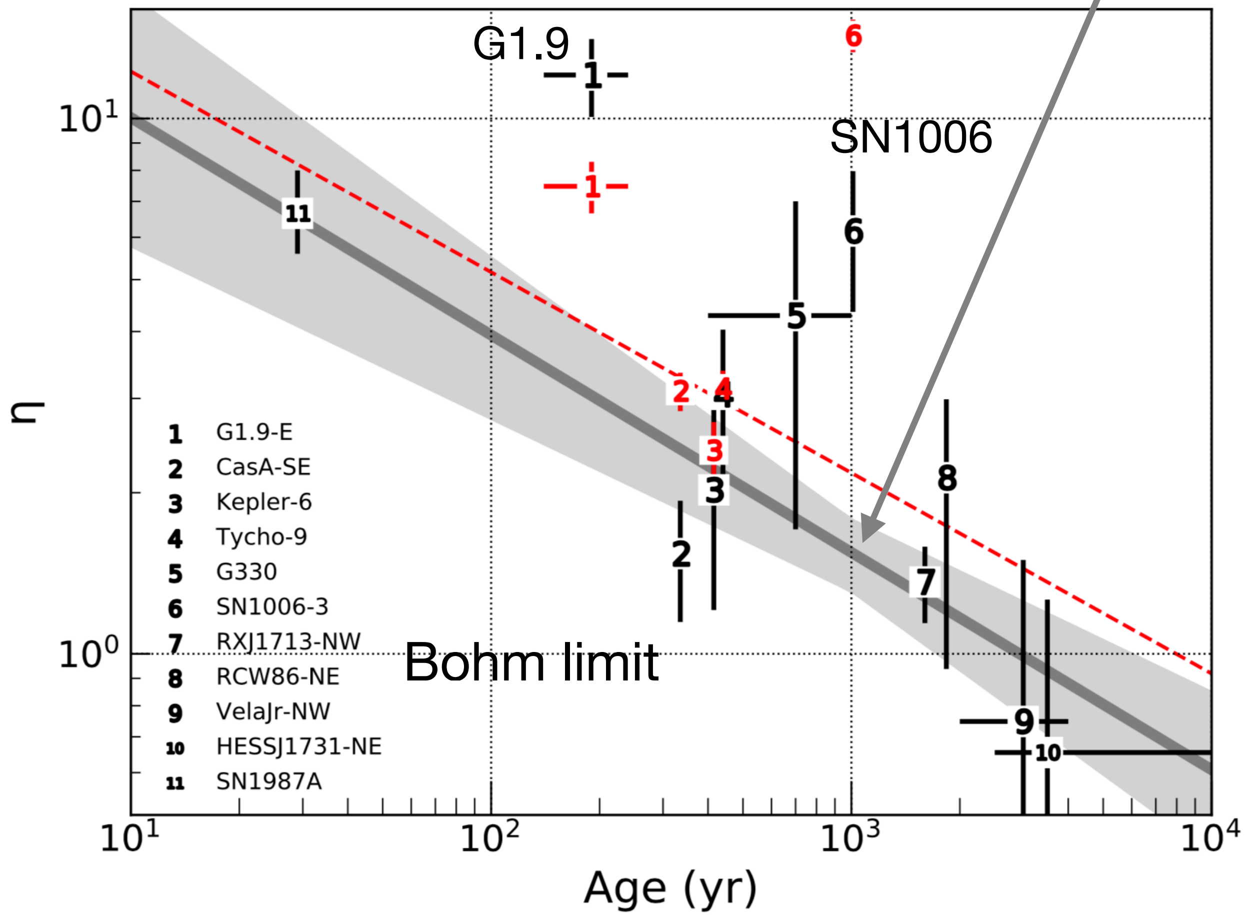
- Cutoff - shock speed relation
  - A variety (many kinds) of particle acceleration
  - See Tsuji+ 2020 for detail

Acceleration efficiency in young SNRs

※ Note: Forward-shocked
max-ε_0 (max-V_{sh}) regions

$\eta = 1.5\ (t_{age}/1\ \mathrm{kyr})^{-0.4}$

Turbulent level	Acceleration
weak	inefficient
↕	↕
strong	efficient



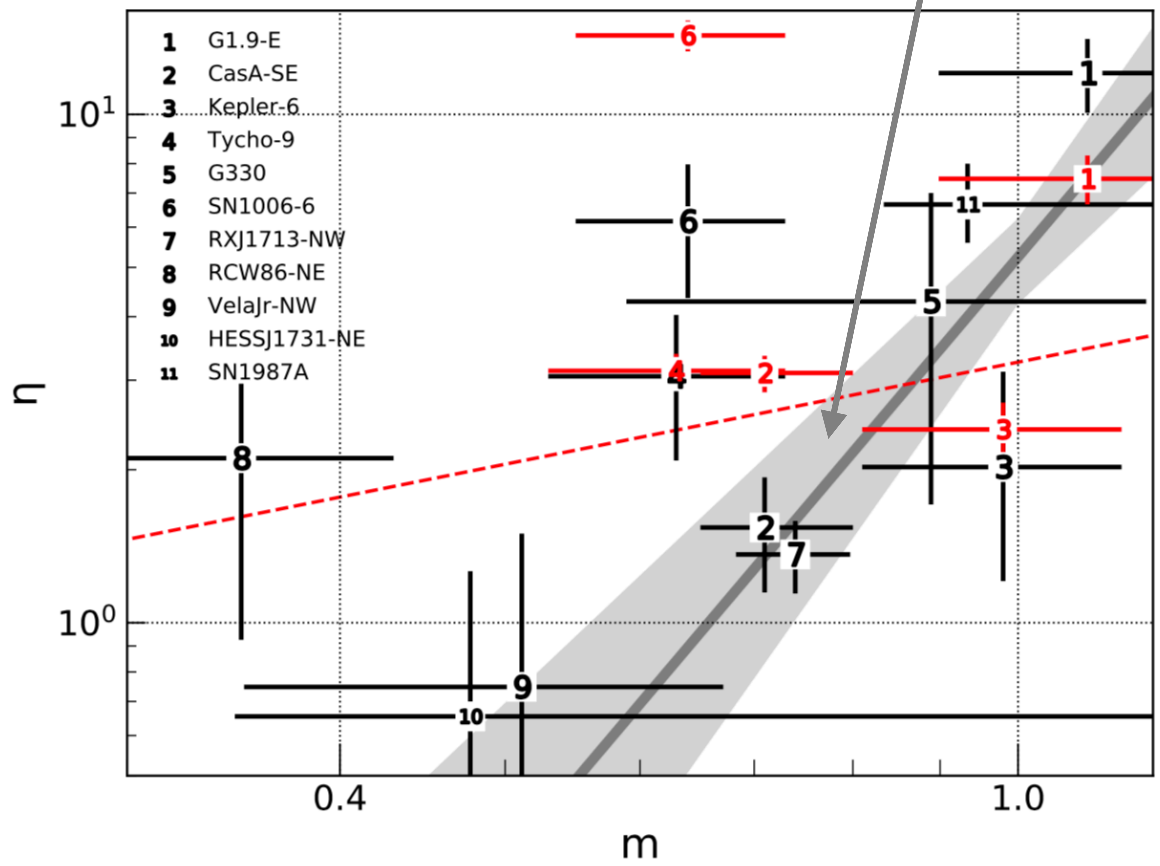
- Evolution of η:
  - Acceleration is more efficient (small η) in older (~kyr) SNRs
  - could be related to turbulent production

Acceleration efficiency in young SNRs

※ Note: Forward-shocked max-ε_0 (max-V_{sh}) regions

$\eta = 5.2\ m^{-4}$

Turbulent level	Acceleration
weak	inefficient
↑	↑
↓	↓
strong	efficient



- Evolution of η (expansion parameter v.s. η):
  - Acceleration is more efficient (small η) in older (m~0.4) SNRs
  - could be related to turbulent production

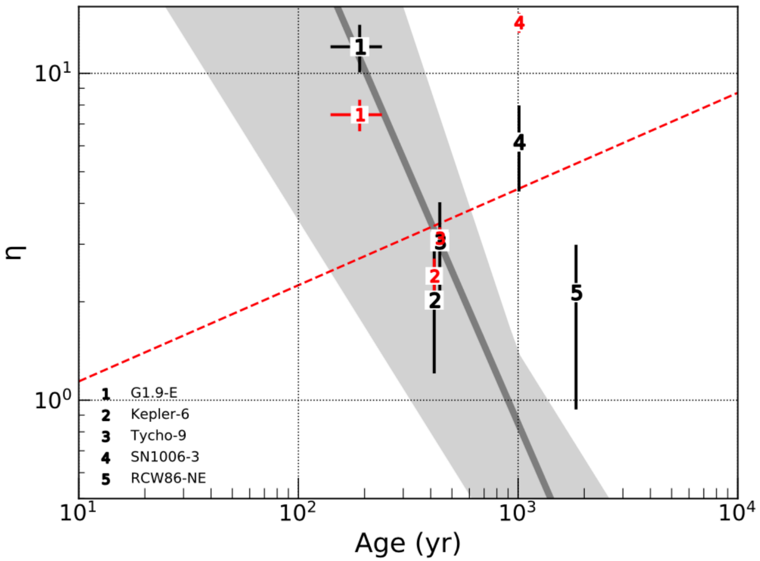
Acceleration efficiency: type Ia & II

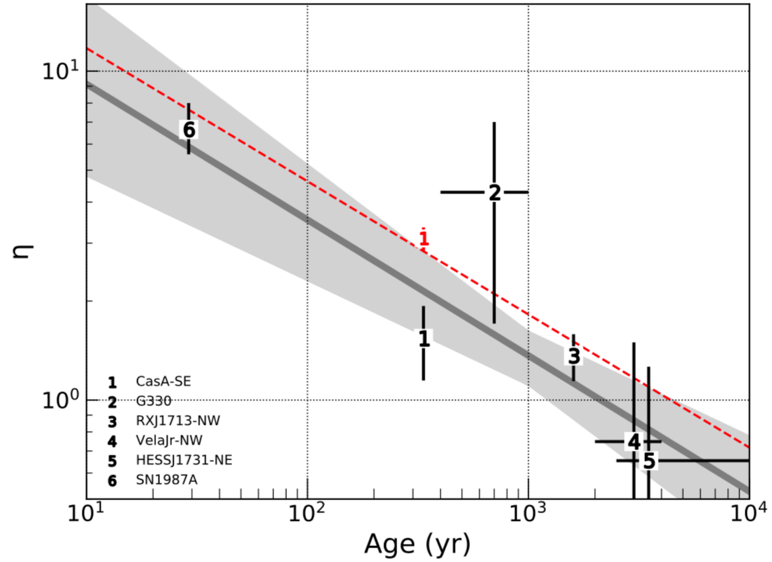
Type Ia

G1.9, Kepler, Tycho, SN1006, RCW86

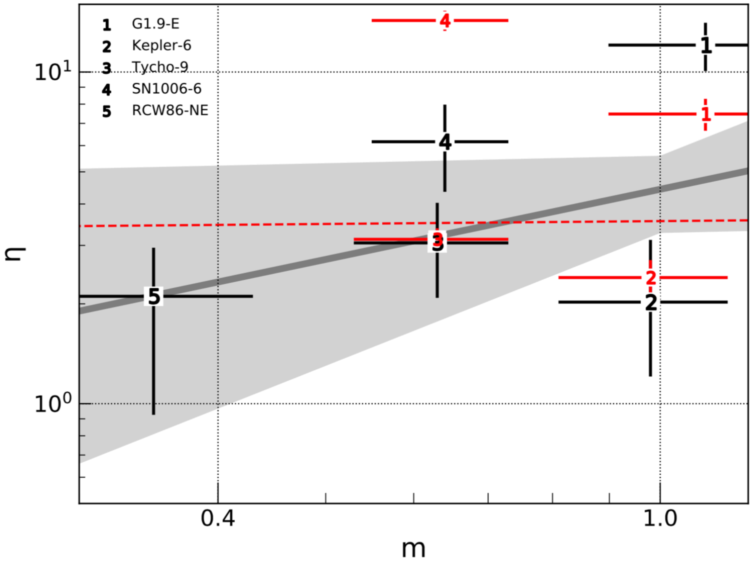
Type II

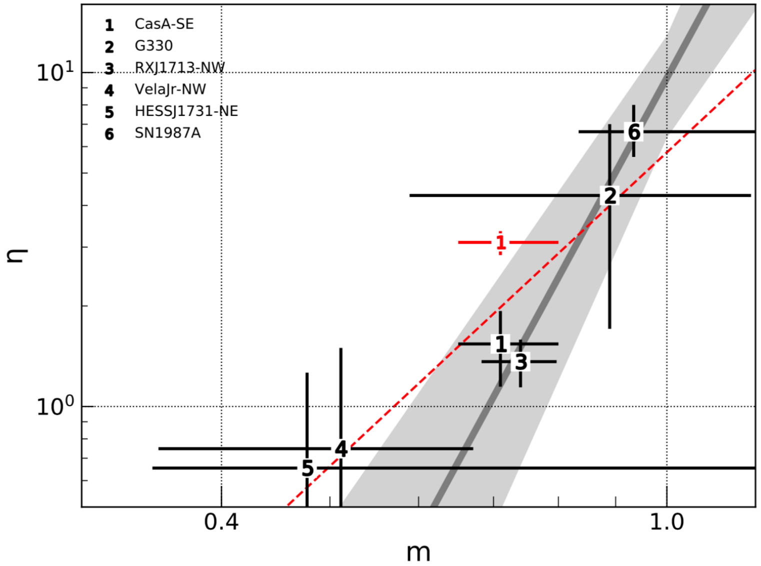
Cas A, G330, RXJ1713, Vela Jr., HESS J1731,1987A





← age-η →





← m-η →

Maximum energy

Age-limited maximum energy: $$E_{\mathrm{max,age}} = \frac{Zq}{c} t v_{\mathrm{sh}}^2 B \eta^{-1}$$

Shock speed: $$v_{\mathrm{sh}} \propto \begin{cases} t^0 & \text{(Free-expansion phase)} \\ t^{-3/5} & \text{(Sedov-Taylor phase)} \end{cases}$$

Magnetic field: $B \propto t^{-\mu}$

$$\mu = \begin{cases} 0 & \text{(Free-expansion)} \\ 0.55 - 0.9 & \text{(Sedov-Taylor)} \end{cases}$$

(Bamba+ 2005; Volk+ 2005; Vink 2008)

Bohm factor: $\eta \propto t^{-\delta}$ (δ~0.46; this work)

$$E_{\mathrm{max,age}} \propto \begin{cases} t^{1-\mu+\delta} & \text{(Free-expansion)} \\ t^{-1/5-\mu+\delta} & \text{(Sedov-Taylor)} \end{cases}$$

- Assume that η evolves as $\eta \propto t^{-\delta}$ at free-expansion/ST stages before η=1
- Max energy can be higher than expected before (δ=0)

Application to gamma-ray observation

Model (electron)

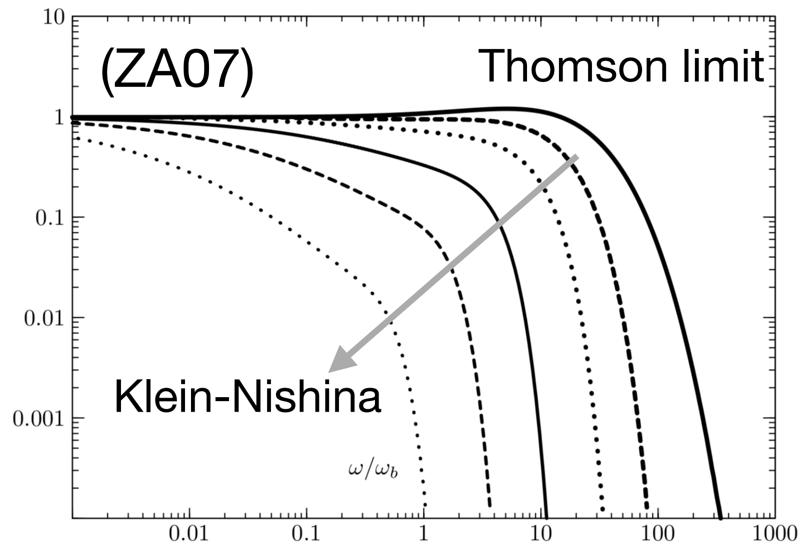
- SNR shock
- Zirakashvili & Aharonian 2007 (ZA07)
- Energy loss: synchrotron cooling
- Diffusion: Bohm type

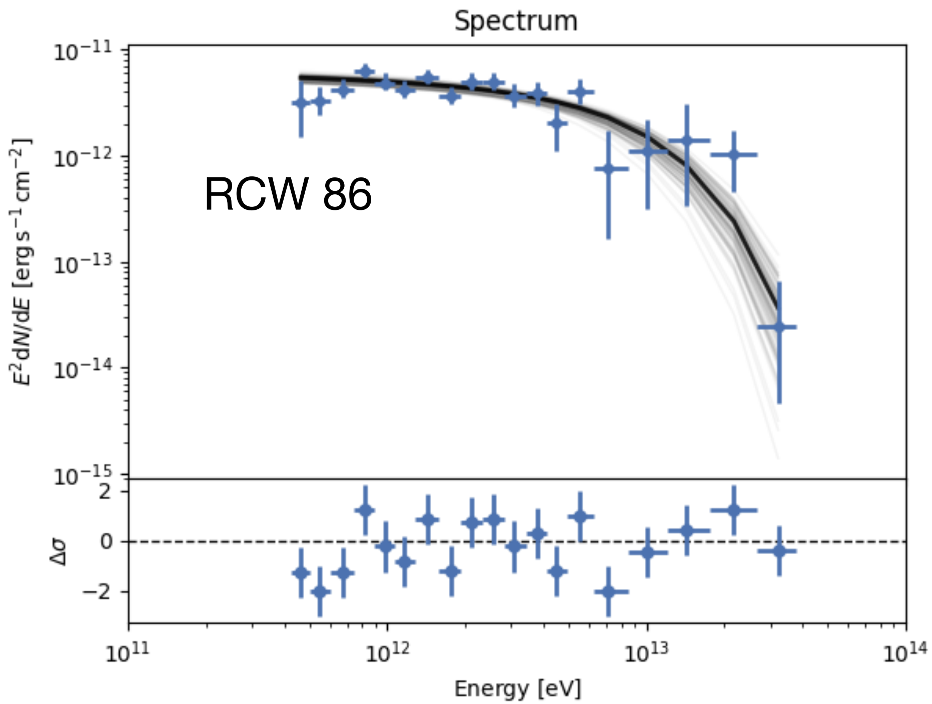
Model (gamma-ray)

Inverse Compton scattering
(in KN regime using Naima)

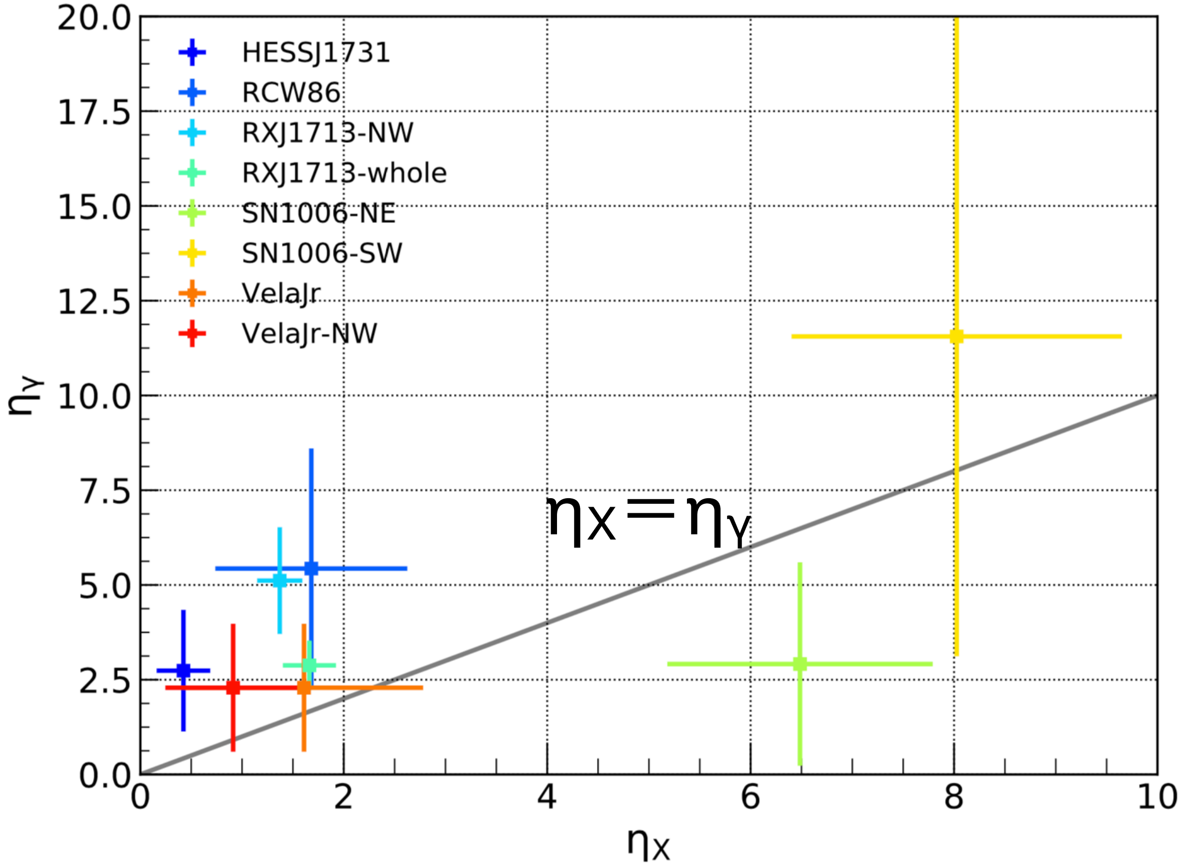
Observation

e.g.) RCW 86-whole (w/ H.E.S.S.)
Cutoff energy (electron): 26 TeV
Shock speed: ~3000 km/s (Yamaguchi+ 16)
B-field: ~10 uG (Ajello+ 16)
→Bohm factor: η~8





Bohm factor: X-ray and γ-ray observations



- η can also be estimated from gamma-ray spectra
- Issues: different regions for X-ray and gamma-ray spectra and/or assumption of leptonic origin
- More constrained with spatially resolved gamma-ray observations (Cherenkov Telescope Array; CTA)

Summary

- Particle acceleration in SNRs can be characterised by cutoff, shock speed, acceleration efficiency (η; Bohm factor), etc.

✤ X-ray observations
- Systematic analysis of 11 young SNRs
  - Measurement of cutoff energy
  - Various types of cutoff-Vshock relation
  - The more efficient acceleration for the older SNR

✤ Gamma-ray observations
- Measurement of cutoff energy
- Prospect for CTA